



## An Improved Mathematical Modelling of Directivity for Radial Line Slot Array Antenna

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# An Improved Mathematical Modelling of Directivity for Radial Line Slot Array Antenna

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## Abstract

This submission formulates a more realistic mathematical model for directivity evaluations of RLSA antennas. It addresses both the effects of aperture and slots concentrations on the aperture in formulating a precise directivity evaluation relationship looking at the 3dB half power beamwidth (3dB-HPBW) and slot surface area. CST MWS suite's simulations results of varying aperture and slots sizes were recorded. MATLAB regression tool was used for the computations to obtain a best fit polynomial evaluation equation for the 3dB HPBW in  $E$  and  $H$  planes respectively. The best fit polynomial was expressed as a function of slots surface area  $f(A)$ . Results computed were compared with those obtained from previous study and showed 5% directivity evaluations improvement. This affirms that the combine contributions from slots area concentrations and the aperture of an RLSA antenna gives a more realistic directivity evaluation than the consideration of only the RLSA aperture.

**Keywords:** Mathematical modelling, directivity, RLSA antenna, regression

## 1. Introduction

Mathematical models are used to express explicitly the performance of antenna. Over the years efforts have been made to obtain more realistic mathematical equations that define the directivity of antenna. Balanis (2005) formulated directivity formula for aperture antenna considering  $3dB$  HPBW for  $E$  and  $H$  planes respectively. This was achieved by the way of formulating equation for aperture antennas that made the products of  $E$  and  $H$  planes to be inversely proportional to the directivity as seen in equation 1.1. This directivity formula works well for apertures antennas. However,  $3d$  BHPBW at  $E$  and  $H$  planes respectively, and antenna aperture do not describe well enough the radiation behaviour of RLSA antenna that has radiating slots (Solomon, 2015).

$$D_o = \frac{32,400}{\Theta_{Ed} \cdot \Theta_{Hd}} \quad (1.1)$$

$D_o$  Represents the directivity,  $\Theta_{Ed}$  represents the  $3d$  BHPBW Electric field plane, and  $\Theta_{Hd}$  represents the  $3d$  BHPBW magnetic field plane.

Further directivity studies of the RLSA antenna looking at the slot width variations, and the radiation contribution of each slot was looked into by Solomon *et al.* (2014). The authors used regression model to model the directivity formula for RLSA antenna as a function of slot width and  $3dB$  HPBW. This technique describes better the directivity of a typical RLSA antenna that has considered, beyond just aperture, and  $3dB$  HPBW, the slot widths and its radiation effect which when summed up, describes better, the directivity of a typical RLSA antenna. However, the slot of an RLSA antenna is rectangular and the surface area has not been considered. Graphical representation of a typical RLSA antenna, and its slot is seen in figure 1.1 and 1.2 below:

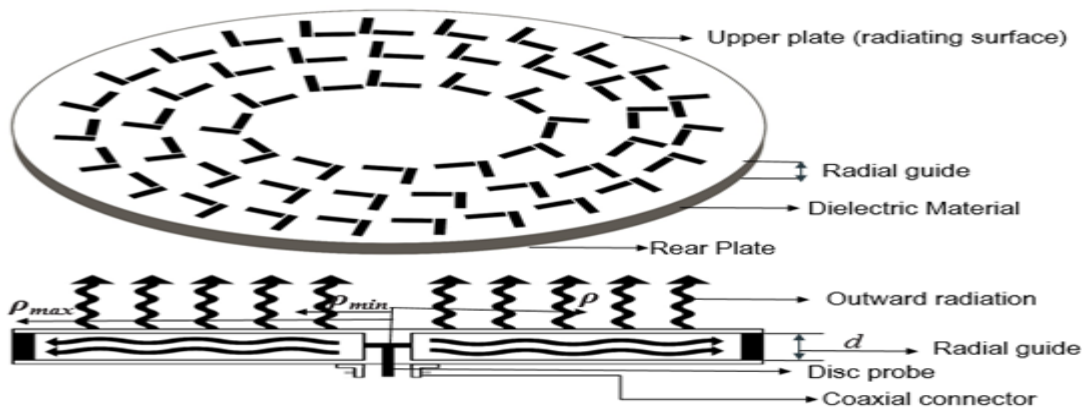


Figure 2.1 The Single layer of the RLSA Antenna Feeder and Radial guide (Islam, 2007)

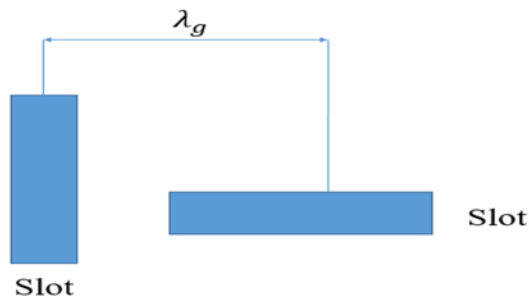


Figure 2.2: Slots Pair (Solomon, 2015)

## 2. Directivity Formula for RLSA Antenna

The relationship that exists between dependent and independent variables can be obtained using regression statistical model coupled with the fact that MATLAB regression offers simplicity, accuracy, for regression analysis, hence, it has so been chosen to simulate this work.

The steps that achieve this research are itemized as follows;

1. Conventional directivity formula is used and improved upon in this study.
2. Data set of previous study is used in the formulation of improved directivity formula of RLSA antenna based on slot area consideration. This work takes cognisance of the slot surface area on the radiation surface (copper plate) for a better directivity description of a typical RLSA antenna as a follow up to conventional directivity formula used for aperture antennas.
3. Slot length of this variation (Length = (1.25:1.25:23.75)) is considered and used for the computation of the slots area used for this study.
4. MATLAB Regression simulation tool is used for the evaluations of the 3 dB PHBW function at  $E$  and  $H$  planes respectively to generate a new function that considers slots area on the aperture of the RLSA antenna. Lines of best fits is chosen to obtain the possible best function that is used in formulating the products of the 3 dB PHBW in  $E$  and  $H$  planes.
5. The product of these new functions is then used in the denominator of the conventional directivity formula to formulate the improved mathematical model for RLSA antenna.
6. Comparison is made between the newly computed directivity function and the previous studies with a view to showing the improvement achieved by this study.

The Table 1 shows the data obtained from previous study Iliya *et al.* (2014).

This Table 1 shows the slots width variation, the 3 dB PHBW at  $E$  and  $H$  planes respectively generated using CST simulation, and their directivity values with 12 slots number considered.

Table 1 Computations from CST MWS in the Previous Work

SLOT WIDTH(MM)	DIR (dBi):N=12	$\Theta_{Hd}$ (deg)	$\Theta_{Ed}$ (deg)
0.25	8.25	1.2	1.3
0.5	25.6	1.2	2.5
0.75	29	1.3	2.7
1	32.9	2.5	2.4
1.25	31.3	4	2.5
1.5	32.2	3.6	2.5
1.75	32.1	3.2	2.4
2	31.8	2.9	2.4
2.25	31.5	2.3	2.5
2.5	31.3	2.1	2.6
2.75	31.1	2.5	2.6
3	30.7	3.0	2.9
3.25	31.7	2.4	2.9
3.5	30.6	3.5	2.9
3.75	30.6	2.7	3.1
4	29.9	2.3	3.2
4.25	29.3	2.2	3.4
4.5	28.9	2.2	3.5
4.75	27.2	5.5	3.2

### 2.1 Development of the Improved Model

Numerical expression for directivity ( $D_o$ ) has been formulated in the literature by Balani (2005), Davis (2000) and Zagghoul *et al.* (2001), it expresses directivity for aperture antenna to be as inversely proportional to product of *3dB HPBW in the electromagnetic plane* as seen in equation 2.1: Balanis (2005)

$$D_o = \frac{32,400}{\Theta_{Ed} \cdot \Theta_{Hd}} \quad (2.1)$$

$D_o$  represents the directivity,  $\Theta_{Ed}$  represents the *3d BHPBW Electric field plane*, and  $\Theta_{Hd}$  represents the *3d BHPBW Magnetic field plane*.

The directivity formula in equation 2.1 is the conventional directivity formula, and it is well suited for aperture antenna, nevertheless, for RLSA antenna, it has not considered at all the impact and the presence of the slots that produce the radiation. Iiyya *et al.* (2014) considered the width of the slot that produced the radiation, measured its implications on the *3dB HPBW in the electromagnetic plane*, and formulated a function to describe how *E* and *H* planes varies with the slot width. 12 slots in the first ring were used to carry out this work. The product of the functions generated for the *3dB HPBW E* and *H* planes upon computations based on slot width, was then taken into the conventional directivity formula to formulate the directivity for RLSA antenna based on slot width variations.

The mathematical analysis of what was done by Iiyya *et al.* (2014) is expressed in equation 2.2 and equation 2.3

$$D_o = \frac{32,400}{f(w)} \quad (2.2)$$

$$(\Theta_{Ed}) * (\Theta_{Hd}) = f(w) \quad (2.3)$$

Where:

$\Theta_{Hd}$  = *3dB HPBW Magnetic plane*

$\Theta_{Ed}$  = *3dB HPBW Electric plane*

$w$  = (0.25: 0.25: 4.75);

This research has considered the fact the typical slot of RLSA antenna is rectangular, which implies that it has length and width, slot area has been computed and related to the *3dB HPBW in the electromagnetic plane*, and has been used within microwave frequency for any possible slot number. Slot area is then used to generate the new function that describes better, the directivity of a typical RLSA antenna.

In the equation 2.5, the surface area of the slot of RLSA antenna is a function of the *3dB HPBW* for Electric Field and Magnetic Field planes respectively.

$$D_o = \frac{32,400}{f(A)} \quad (2.4)$$

$$(\Theta_{Ed}) * (\Theta_{Hd}) = f(A) \quad (2.5)$$

Where:  $\Theta_{Hd}$  is *3dB HPBW, magnetic plane*

$\Theta_{Ed}$  is *3dB HPBW electric plane, A is Slot Area(mm<sup>2</sup>)*

MATLAB regression tool is used to generate the requisite function, which is a polynomial function of 6<sup>th</sup> order for the *3dB HPBW* for E (Electric Field) and H (Magnetic Field) planes respectively, the 6<sup>th</sup> order represents the

best fittings for the data as in table 2 and is used to eventually compute the improved directivity formula for the RLSA antenna. The requisite function as seen in figure 3.3 and 3.4 best describe the relationship between the 3dB HPBW in the electromagnetic plane and the slot area.

## 2.2 The Improved Directivity Function

Physical length of the slot ranging from  $L = (1.25:1.25:23.75)$  has been considered for this research. This range of length variation has been carefully chosen based on the various designs done on RLSA antenna. For example Jiro (1989) utilized (slot length 10mm, and slot width 1mm), in his RLSA antenna design. Purnamirza (2012) used (slot length  $0.5\lambda_g$ , and slot width 1mm) for the RLSA antenna he fabricated, Illiya (2015) adopted (slot length  $0.5\lambda_g$ , and slot width 1mm) in his RLSA antenna design, Kamaruddin (2015) utilized (slot length 5mm, and slot width 1mm). The table 2 shows the formulation of the slot area for the study.

Width = (0.25:0.25:4.75) and Length = (1.25:1.25:23.75)

Table.2: Slot Area Computation

SLOT WIDTH (MM)	SLOT LENGTH (MM)	SLOT AREA WIDTH*LENGTH (MM <sup>2</sup> )	$\Theta_{Hd}$ (DEGREES)	$\Theta_{Ed}$ (DEGREES)
0.25	1.250	0.3125	1.2	1.3
0.50	2.500	1.25	1.2	2.5
0.75	3.750	2.8125	1.3	2.7
1.00	5.000	5.0	2.5	2.4
1.25	6.250	7.8125	4	2.5
1.50	7.500	11.25	3.6	2.5
1.75	8.750	15.3125	3.2	2.4
2.00	10.00	20	2.9	2.4
2.25	11.25	25.3125	2.3	2.5
2.50	12.50	31.25	2.1	2.6
2.75	13.75	37.8125	2.5	2.6
3.00	15.00	45	3.0	2.9
3.25	16.25	52.8125	2.4	2.9
3.50	17.50	61.25	3.5	2.9
3.75	18.75	70.3125	2.7	3.1
4.00	20.00	80	2.3	3.2
4.25	21.25	90.3125	2.2	3.4
4.50	22.50	101.25	2.2	3.5
4.75	23.75	112.8125	5.5	3.2

### 2.3 Regression Analysis

MATLAB regression tool is used to fit the computed data (slot area and the 3dB HPBW in the electromagnetic plane) as seen in table 2 to a curve that best describe the relationship between the 3dB *HPBW* in the E and H planes and the slot area. Essentially, this analytical tool generates new functions by minimizing the sum of squared difference between the original data set, and the fit function to obtain the improved polynomial function. This work considers 6<sup>th</sup> order polynomial function in the formulation of the new directivity function because, 6<sup>th</sup> order delivers the best fits for the curve that describes the relationship between the 3dB HPBW in the electromagnetic plane, and the slots area.

Figures 3.3 and 3.4 present the improved 3dB HPBW function of the study.

### 3. Results

The results of this research are displayed in Figures 3.1, 3.2 and 3.3, 3.4.

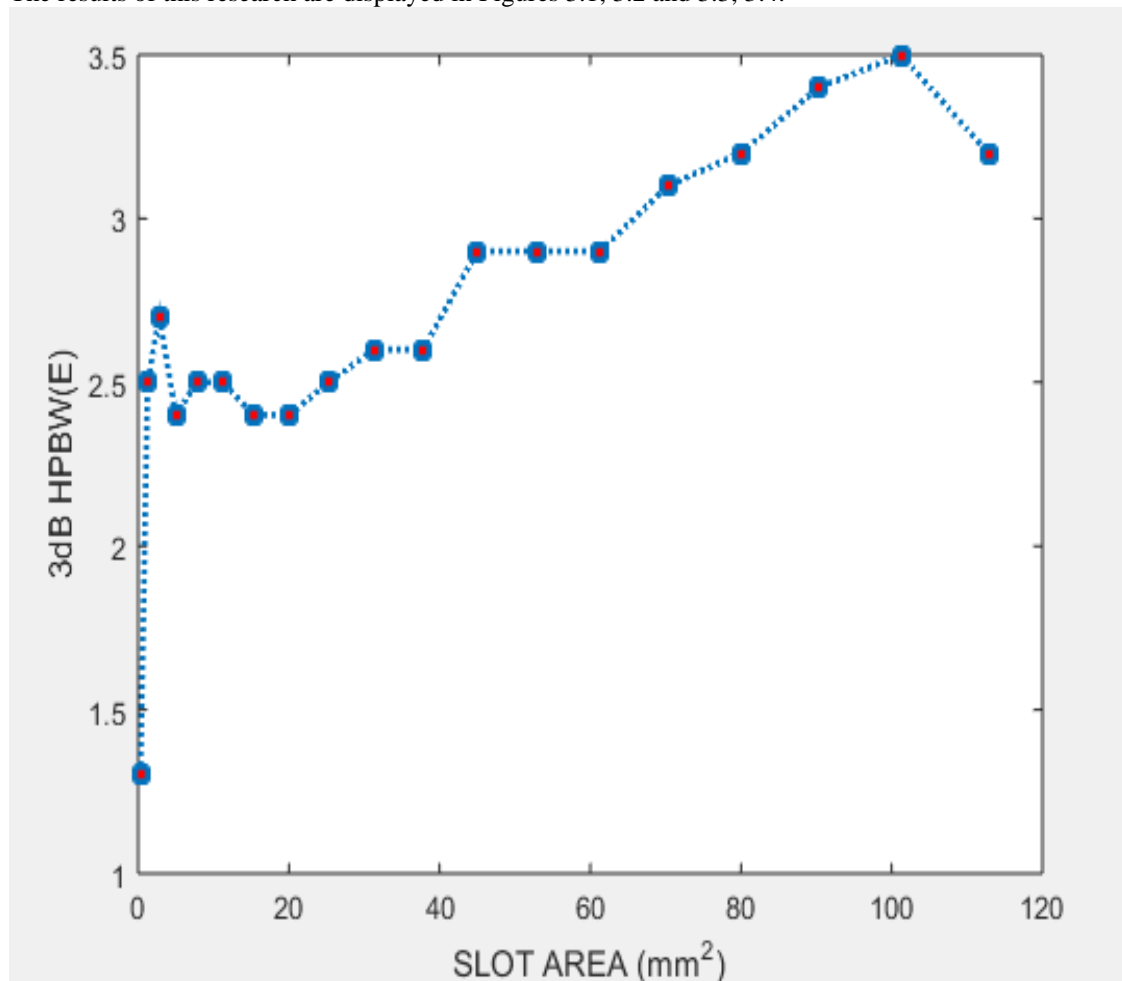


Figure 3.1 Slots Area and 3dB HPBW (degrees) E-planes

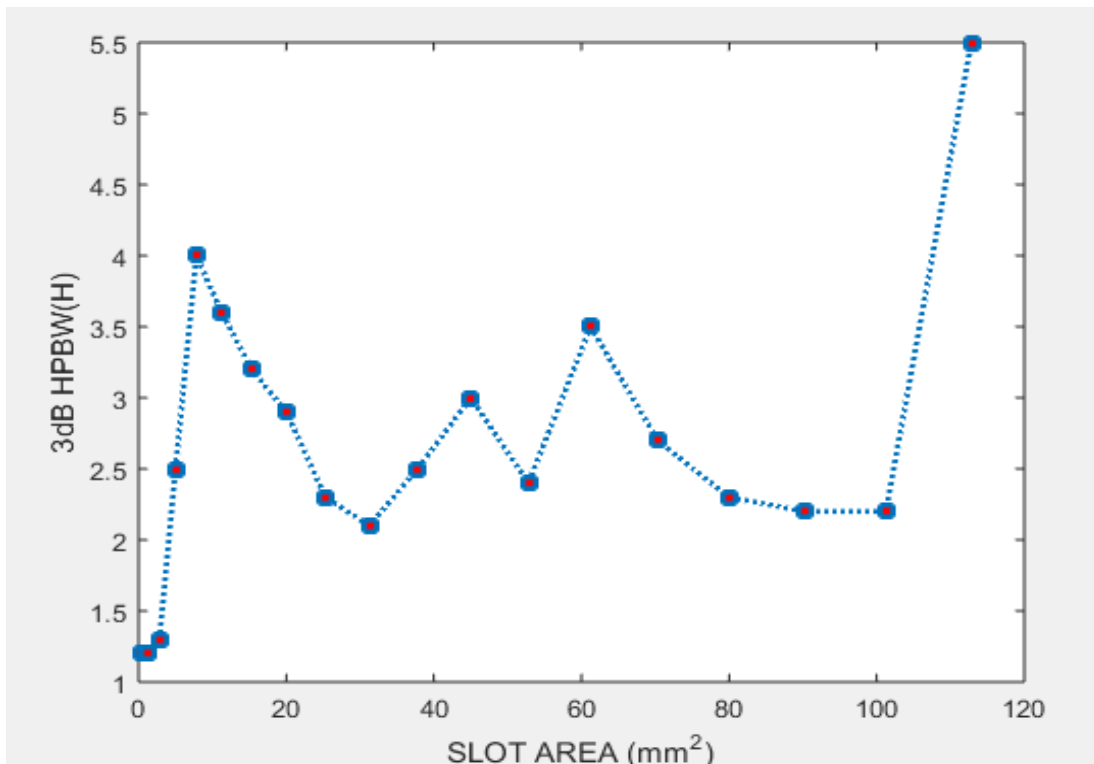


Figure 3.2 Slots Area and 3dB HPBW (degrees) H-planes

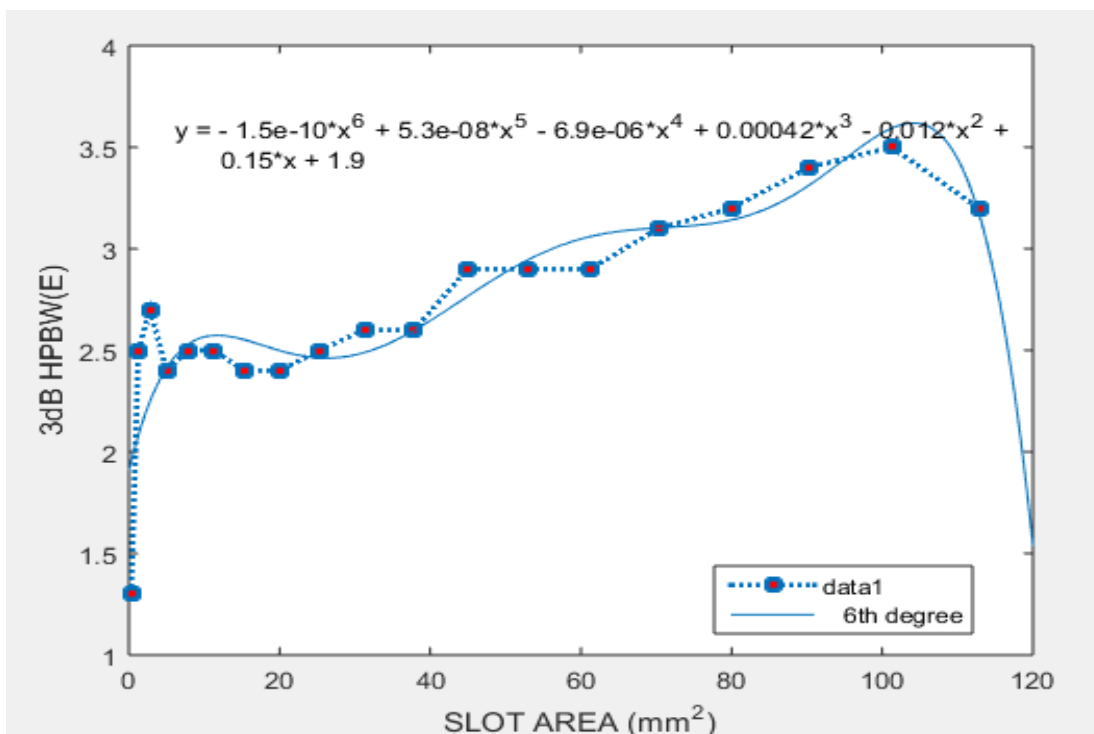


Figure 3.3 Generated function for Slots Area and 3dB HPBW (deg) E-planes

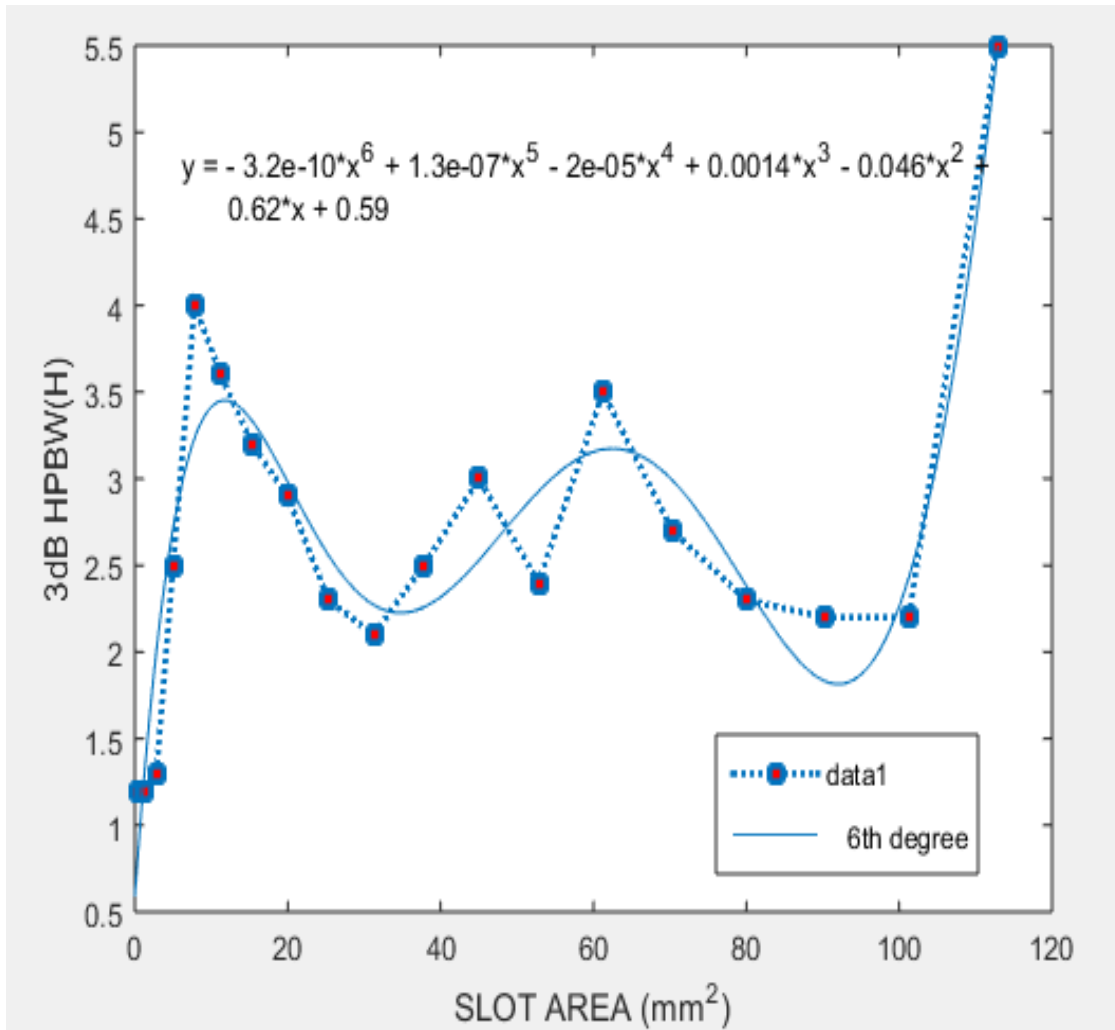


Figure 3.4 Generated function for Slots Area and 3dB HPBW (deg) H-planes

### 3.1 Results Interpretation

Figures 3.1 and 3.2, show the implication of the slots area variations on the *3dB HPBW* in the electromagnetic plane for RLSA antennas. Essentially, *3dB HPBW* in the electromagnetic plane is used to measure the directivity of antenna. The graphs strengthen the known fact that it will not be enough, to measure the directivity of RLSA antennas, without considering the area of the slots that actually produce the radiation. Figures 3.1 and 3.2 shows that the variations in the slots area on the aperture of a typical RLSA antenna, create variation in the *3dB HPBW*, which ultimately affect the directivity of the antenna. Figures 3.1 and 3.2 also show the orthogonality that characterizes electromagnetic wave.

Figures 3.3 and 3.4 show the results of the MATLAB regression analytical tool. These figures display the line of best fits, the curve fittings, and the new function that has factored in slots area on the aperture of RLSA antenna. The slot area is the result of the product of the introduced slot length and the slot width obtained from the literature. Essentially as discussed earlier, the regression tool performs the task of minimizing the sum of the squared difference between the original data points, and the fit function to generate the new function for the *3dB HPBW* in the electromagnetic plane with due consideration of the slots area in the formulation of the function. The improved functions from the Figure 3.3 and 3.4 are presented in equation 3.1 and equation 3.2 respectively.

$$\Theta_{Hd} = -0.00000000032A^6 + 0.00000013A^5 - 0.00002A^4 + 0.0014A^3 - 0.046A^2 + 0.62A + 0.59 \quad (3.1)$$

$$\Theta_{Ed} = -0.00000000015A^6 + 0.000000053A^5 - 0.0000069A^4 + 0.00042A^3 - 0.0126A^2 + 0.15A + 1.9 \quad (3.2)$$

Also, as stated in chapter one, given that;

$$D_o = \frac{32,400}{\Theta_{Ed} \cdot \Theta_{Hd}} \quad (3.3)$$

Where:

$$\Theta_{Hd} = H_{-plane} \text{ 3dB HPBW}$$



$$\Theta_{Ed} = E_{-plane} 3dB \text{ HPBW}$$

Substituting equation 3.1 and equation 3.2 into equation 3.4, using the values of slots Area (A), we have the improved directivity function for RLSA antenna.

$$D_o = \frac{32,400}{f(A)} \quad (3.4)$$

Equation 3.4 is the improved directivity formula for RLSA antenna. This formula has most importantly factored in the surface area of the slots on the radiating surface that actually produces the radiation. Numerical computations are seen below:

$$\Theta_{Hd} = -0.00000000032(0.3125)^6 + 0.00000013(1.25)^5 - 0.00002(2.8125)^4 + 0.0014(5)^3 - 0.046(7.8125)^2 + 0.62(11.25) + 0.59$$

$$= 4.931131798 \text{ deg.}$$

$$\Theta_{Ed} = -0.00000000015(0.3125)^6 + 0.000000053(1.25)^5 - 0.0000069(2.8125)^4 + 0.00042(5)^3 - 0.0126(7.8125)^2 + 0.15(11.25) + 1.9$$

$$= 2.90714655 \text{ deg.}$$

$$(\Theta_{Ed}) * (\Theta_{Hd}) = f(A)$$

$$f(A) = 2.90714655 * 4.931131798 = 14.33552279 \quad (3.5)$$

Substituting equation 3.5 into equation 3.4 we have;

$$D_o = \frac{32,400}{f(A)} \quad (3.6)$$

$$D_o = \frac{32,400}{14.33552279} = 2260.119876 = 10 \log(2260.119876)$$

$$D_o = 33.54131475 \text{ dBi}$$

Table.3 Results Comparison

CST SIMULATED DIRECTIVITY (dBi) Iliya <i>et al.</i> (2014)	REGRESSION ANALYSIS SIMULATED DIRECTIVITY (dBi). Iliya <i>et al.</i> (2014)	DIRECTIVIT Y (dBi) FROM STUDY.	DIRECTIVITY FROM CONVENTIONAL FORMULA (dBi) <i>Solomon I. Z. (2015)</i>
32.9	31.94	33.54	37.32

### 3.2 Discussions

Following the mathematical computations using slots area, the improved modeled formula for RLSA antenna achieved directivity  $D_o = 33.54 \text{ dBi}$ . This shows a good agreement with the CST simulated directivity whose directivity is  $D_o = 32.9 \text{ dBi}$ . The difference of  $0.64 \text{ dBi}$ , is attributed to the fact that CST simulated directivity resulted from a directivity model that considered slots width variations, and has not taken into cognizance the effects of slots area on the radiation surface.

The directivity ( $D_o = 33.54 \text{ dBi}$ ) obtained from the improved formula for this study also shows good agreement with the directivity (dBi) from previous study Iliya *et al.* (2014, 2015), where slot width was considered. The previous study achieved directivity  $D_o = 31.94 \text{ dBi}$ . The  $1.6 \text{ dBi}$  difference seen when juxtaposed with result of this study is due to the fact that previous study Iliya *et al.* (2014, 2015), only considered the width of the slots as against slot area considered by this research.

Conventional directivity formula achieved directivity  $D_o = 37.2 \text{ dBi}$ . There is a wide difference of  $3.66 \text{ dBi}$  when compared with the directivity ( $D_o = 33.54 \text{ dBi}$ ) obtained from this study. This difference, as established, by previous studies, is due to the fact that conventional formula has only considered the aperture and the **3dB HPBW** in the electromagnetic plane, the conventional formula has factored-in neither the slots width, nor slots length, nor slots area on the aperture. Hence this research has achieved an improved mathematical model for directivity of RLSA antenna with convincing results.

### 4. Conclusion

This work has therefore achieved an improved directivity formula suitable for the RLSA antennas. Formulation of the improved directivity formula for RLSA antenna was realized considering the aperture, 3dB

HPBW in the electromagnetic plane, and slot surface area. This work viewed that the slot of a typical RLSA antenna is rectangular, and hence has length and width which when computed produced the surface area of the slot. Essentially slot area was used to produce improved functions for the 3dB HPBW half power beamwidth in the electromagnetic plane, which was eventually used to produce the improved mathematical model of directivity for RLSA antenna.

The directivity result of 33.54 (dBi) obtained for this study using MATLAB regression showed that slots area have great effect on the directivity of RLSA antenna and overall radiation performance as compared with the directivity result of previous study that has considered the width variation of the slot of RLSA antenna that has 31.94 (dBi) as its directivity. This further establishes that considering the slots area of RLSA antenna in modeling its directivity, describes better its directivity.

#### **4.1 Further Work**

Sharp variation was noticed in the radiation behaviour of RLSA antenna in the electromagnetic plane as revealed by the result of this research at slot length 22.50mm & slot width 4.50mm which produced slot area 101.25mm<sup>2</sup>, this strange phenomenon can be investigated by researchers. Also, poor return loss in linearly polarized RLSA especially in the areas of DBS applications is open to investigation.

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